ASSESSMENT OF RADAR ALTIMETER PERFORMANCE WHEN USED FOR INTEGRITY MONITORING IN A SYNTHETIC VISION SYSTEM

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Abstract

Synthetic Vision Systems (SVS) are being developed to support a wide variety of operations [1]. These operations include tactical or critical applications of the SVS. To enable certification of an SVS as a flight-critical system several requirements the system must be met with regards to accuracy, integrity, availability, and continuity. Ohio University has been developing a prototype SVS as part of NASA's aviation safety program that includes a real-time terrain database integrity monitor to guarantee the required integrity. Ohio University's integrity monitor provides a consistency check between a terrain database profile and a synthesized terrain profile. The synthesized terrain profile is generated from information from Global Positioning System (GPS) and a radar altimeter. This paper explores the radar altimeter performance for use in a SVS terrain database integrity monitor. Test flights conducted by Ohio University with the DC-3 flying laboratory and by NASA with the Total In-Flight Simulator (TIFS) aircraft have provided several hours of flight data. This data will be used in this paper to assess the various radar altimeters. Data from two different radar altimeters and a highly accurate photogrammetry digital elevation models (DEM) are used to evaluate the performance of the radar altimeters. The effects of the terrain variation underneath the aircraft and the radar altimeter antenna beamwidth on the performance of the radar altimeter are discussed. The other topics in this paper provide a general understanding of the operation of radar altimeters and discuss operational limitations of the standard radar altimeters when used as part of SVS integrity monitoring schemes.

Introduction

When using sensor data, it is important to characterize what the sensor truly measures. This obvious statement is the driving force behind this paper. When designing an integrity monitor for a terrain database used in an SVS, the information from the radar altimeter is used to create a synthesized terrain profile in the real time. The synthesized terrain profile is then compared to a database profile, which is generated from a lookup in the terrain database based on the aircraft's position. When designing this integrity monitor an assumption has been made that the radar altimeter error specifications given by the manufacture are accurate when flying over hilly terrain. Flight tests have shown that, depending on the radar altimeter beamwidth, the height of the aircraft above the terrain, and the terrain roughness, errors can occur that are larger than specified by the manufacturer. If a radar altimeter is to be used as part of a real-time integrity monitor for a terrain database it is important to characterize these error mechanisms.

Synthetic Vision Systems

A Synthetic Vision System (SVS) is envisioned to be a heads down display (HDD) or head up display (HUD), which provides a "from the cockpit" perspective view of the aircraft's current state. Included on the display is information such as attitude, flight path, airspeed, altitude, terrain and more.

[1] describes various operations and scenarios for which SVS is envisioned to be used. Among these operations and scenarios are:

- Controlled-Flight-Into-Terrain (CFIT) prevention,
- Low-visibility surface operations,

- Precision approach and departure (including missed approaches and engine-out takeoffs)
- Recovery from Loss of Control (LOC)

The use of an SVS HDD or HUD will increased Situational Awareness (SA) during these phases of flight and may lead to improved aviation safety.

During various operations described in [1] SVS will be used for tactical decisions by the pilot; if a catastrophic event may occur due to Hazardous Misleading Information (HMI) provided by the display, it is necessary that the system be certified as flight critical. For a system to be certified by the Federal Aviation Administration (FAA) as flight critical it must have certain levels of accuracy, integrity, continuity, and availability. Digital Elevation Models (DEMs) are currently used to generate the terrain imagery in a SVS. DEM examples are the military's Digital Terrain Elevation Data (DTED) or the newly collected terrain database by the NASA Shuttle Radar Topography Mission (SRTM). Currently available terrain databases do not meet the required level of integrity required for tactical use in a flight critical system.

This has led to the research, conducted at Ohio University, on the development of a real time integrity monitor for a SVS terrain database. The concept of having a monitor to increase the integrity of a system has been applied to many of the navigation systems currently in use such as the Receiver Autonomous Integrity Monitor (RAIM), the Local Area Augmentation System (LAAS), and the Wide Area Augmentation System (WAAS).

Downward Looking Integrity Monitor

A downward looking terrain database integrity monitor was first proposed by Dr. Gray [2]. This system provides a consistency check between a terrain profile generated from the terrain database and a synthesized terrain profile. The synthesized terrain profile is generated by subtracting the radar altimeter height Above Ground Level (AGL) from the GPS height above Mean Sea Level (MSL). This principle is depicted in Figure 1.

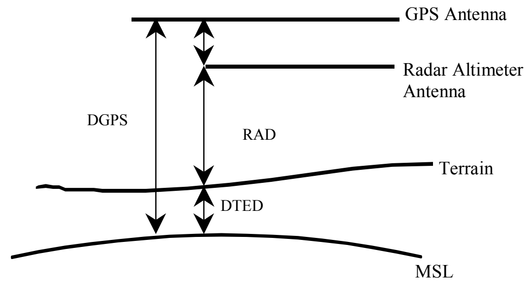


Figure 1. Synthesized Terrain Profile

The consistency between the database profile and the synthesized profile is statistically assessed using a form of the Mean Squared Error (MSE) described in [2]. The integrity monitor parameters such as time to alarm, probability of fault free detection, probability of missed detection, and minimum detectable bias can then be assigned based on the system requirements as shown in [3] and [4]. It should be noted that the downward looking integrity monitor is only directly detecting errors in the vertical direction. Horizontal translational errors map into the vertical direction as a function of terrain [4]

One benefit of the proposed integrity monitor is that it requires minimum retrofit to existing commercial aircraft; it can be implemented using equipment already present on most aircraft.

Something's Cooking… (Flight Test Observations)

Several flight tests have been performed using the proposed integrity monitor, and the results show that the integrity monitor consistently exceeds the integrity threshold at specific locations in the vicinity of the Asheville, NC airport (AVL). The database used in these tests was DTED Level 1 data with 3 arc-second (about 90 meter) post spacing and a standard deviation of 18.2 meters in the vertical direction. Initially it was hypothesized that the database is erroneous on these locations. However, this possibility was eliminated by comparing the DTED data with highly accurate photogrammetry data collected by NASA around AVL. The photogrammetry specifications are a 4-meter post spacing with a Linear Error Probability (LEP) of 1 meter [3]. Flight test data was post processed using the photogrammetry data and it was found that the integrity monitor threshold was still exceeded. This lead to the investigation of the radar altimeter operation over uneven terrain.

The Radar Altimeter

Radar altimeters typically operate in the C radar frequency band with a center frequency at 4.3 GHz. They commonly use separate identical antennas for transmission and reception. These antennas are located on the bottom of the fuselage of the aircraft. Figure 2 the radar altimeter antenna installations on Ohio University's DC-3 test aircraft.

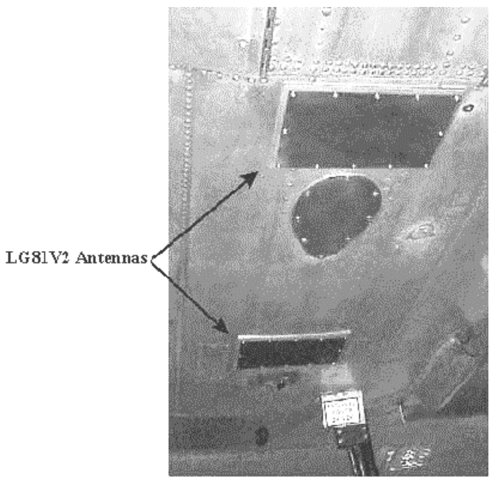


Figure 2. Radar Altimeter Antennas on OU's DC-3

There are two radio modulations commonly used by radar altimeters; FM-CW and pulse. The first type of radar altimeter developed, and most commonly used radar altimeter on Civil Aircraft today, is the FM-CW modulated radar altimeter. Pulse modulation radar altimeters came into use in the 1960's and are more often found on military aircraft. [5]

Typical Specifications

The operating range on most radar altimeters is from 0 ft up to somewhere between 2500 and 5000 ft AGL. Their accuracy specifications are in terms of run-to-run bias, noise, noise as a function of height, and noise as a function of height rate.

The specifications for the radar altimeters investigated in this paper are shown in Table 1.

Table 1. Radar Altimeter Specifications

Type	Altitude Accuracy	Modulation	PRF	BW 3dB
Honeywell HG8505DA01 DC-3 Aircraft	+-3 ft, plus 1%	Pulse	25 kHz	17 deg.
Honeywell HG9050D2 TIFS Aircraft	+-5ft, plus 3% of range, plus 5% of ave. range rate (ft/s)	Pulse	10 kHz	35 deg.
NASA 757	1.0 ft or 2% of range, whichever is greater	FM-CW	N/A	90 deg.

Applications

Radar altimeter utilization on Civil Aircraft today is based on their ability to provide height AGL measurements. The most common application is during the landing phase of flight; with the most critical requirements during an Autoland operation in CAT III conditions. During an Autoland operation the radar altimeter provides height above runway information to the Flight Management System (FMS). Because of the criticality of radar altimeter data to the FMS, triple redundant radar altimeters are typically installed in large civil transports to provide fault tolerance with continued operation. On CAT I or CAT II approaches where Autoland is not used, the radar altimeters can display height AGL to the pilot, who uses it to determine the Decision Height (DH). More recent radar altimeter applications are as source for height AGL and height rate in Ground Proximity Warning Systems (GPWS) and Terrain Awareness and Warning Systems (TAWS). [6]

On all the above applications an average height above the terrain in the radar altimeters beam pattern in sufficient. During Autoland flare, the radar altimeter's beam is completely on the runway so the average distance of all the returns is nearly constant. With the GPWS and TAWS the radar altimeter can be used for height and height rate data; both of these systems are classified as advisory and the exact height AGL is not critical.

Pulse Radar Altimeter

Pulse Radar Altimeters provide height AGL measurements by tracking the time between transmission of a pulse and the reception of its reflection, τ:

$$h_{AGL} = \frac{c * \tau}{2} \qquad (1)$$

where *c* is the speed of light. It can be seen that τ is linearly related to the h_{AGL}. This relationship will be used in the radar altimeter modeling section. In the Honeywell HG8505DA01 and HG9050D2 the leading edge of the return pulse is tracked. This is equivalent to measuring the shortest slant range from the radar altimeter antenna to the terrain below.

The leading edge of the pulse is tracked by generating a pulse just before the expected radar return and multiplying this pulse with the return pulse as seen in Figure 3.

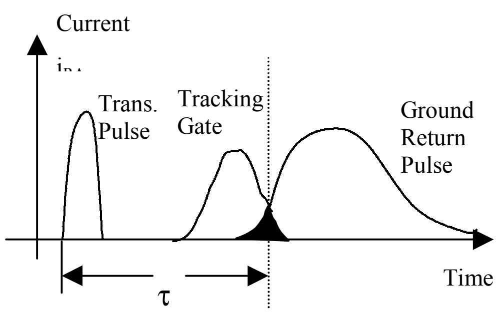


Figure 3. Pulse Radar Range Tracking

There is an overlap area that relates to the range rate and is represented by a current i. The current, i, along with a fixed offset current equal to the normal track current are then integrated to determine the voltage required to be applied to the range integrator. The output of the range integrator represents the range [7]. This information is then used to adjust the position of the leading edge tracking pulse and provides the range (height) measurement.

Because of the range and range-rate integration required to determine the position of the tracking gate, there is a range rate limit, 2000- ft/sec, in the specifications of the examined pulse type radar altimeters [7]. A range error term due to the delay in the feedback loop is also included in pulse type radar altimeters. The range rate error in the radar altimeters used was 5% of the average range rate in ft/sec.

FM-CW Radar Altimeter

The first commercial demonstration of an FM-CW radar altimeter dates back to 1938 [8]. Today FM-CW radar altimeters are the most common radar altimeters used in civil transport aircraft. Unfortunately, flight-data from an FM-CW radar altimeter was not available at the time of this study. FM-CW altimeters measure height by transmitting an FM modulated carrier and measuring the beat-frequency generated by mixing the transmitted signal with the received signal received (after its reflection off the ground). The basic theory of operation is covered in the next section, after which an overview of the operation of the triple redundant radar altimeter on NASA's Boeing 757 is discussed.

A description on the operation of an FM-CW radar altimeter is given to show that the observable, the beat frequency, is linearly related to the height. Figure 4 shows a simplified block diagram of an FM-CW radar altimeter.

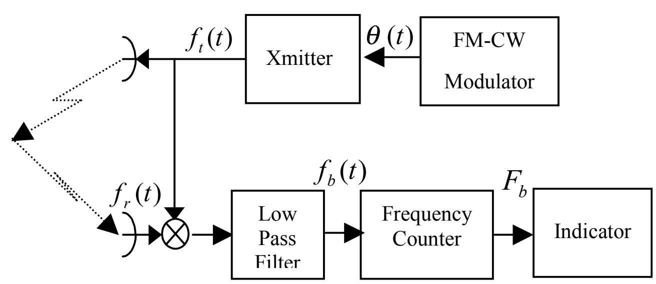
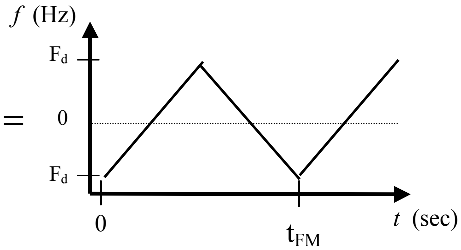


Figure 4. Simplified Block Diagram of an FM-CW Radar Altimeter

The signal transmitted by a typical FM-CW radar altimeter is described by:

$$f_t(t) = A\cos(2\pi\ f_0 + 2\pi\ \theta\ (t)) \qquad (2)$$

where f_0 is the carrier frequency, *A* is the amplitude and is a triangle wave form described as follows:

$\theta\,(t) =$ 

(3)

After reflection of the ground surface, the received can be represented by:

$$f_r(t) = \cos(2\pi\ f_0 + 2\pi\,\theta\ (t + 2h/c)) \qquad (4)$$

where *2h/c* represents the time required for the signal to travel from the transmit antenna, to the ground, and back to the receive antenna.

The received signal is mixed with the current transmit signal yielding:

$$f_t(t) \otimes f(r) = \cos\left[4\pi\ f_o + 2\pi\ (\theta\ (t) + \theta(t + 2h/c))\right] + \cos\left[2\pi\ (\theta\ (t) - \theta(t + 2h/c))\right] \qquad (5)$$

A Low Pass Filter (LPF) is used to separate the beat frequency between the transmitted and received signal leaving the terms:

$$f_b(t) = \cos\left[2\pi(\theta\ (t) - \theta(t + 2h/c))\right] \qquad (6)$$

In (6) the beat frequency, F_b, is $\theta\ (t) - \theta(t + 2h/c)$. This frequency can be represented by:

$$F_b = \frac{2F_d}{0.5t_{FM}} * 2h/c \qquad (7)$$

where t_{FM} is the period of the triangle waveform and F_d is the magnitude of the frequency deviation. This equation is valid for the constant slope portions of the FM modulation. Solving for *h* yields:

$$h = \frac{t_{FM}\,cF_b}{8F_d} \qquad (8)$$

From (8) it is clear that the height is a linear function of the beat frequency, F_b.

The frequency deviation, F_d, for the triple redundant Radar Altimeters on the NASA 757 ARIES is +-50MHz centered on 4.3 GHz carrier. The three radar altimeters avoid interference with each other by operating at different FM modulation frequencies; 95Hz, 100Hz, and 105Hz [9].

Radar Altimeter Modeling

The radar altimeter is used in the downward looking integrity monitor to provide a synthesized terrain profile, which is then compared to the database terrain profile. The basic metric of the integrity monitor is the absolute disparity, defined as:

$$p(t_i) = h_{SYNT}(t_i) - h_{DEM}\left(lat(t_i), lon(t_i)\right) \qquad (9)$$

where h_{SYNT} is the synthesized terrain and h_{DEM} is the value determined from the terrain database. The Synthesized terrain is computed by subtracting the height AGL from the height MSL:

$$h_{SYNT}(t_i) = h_{DGPS}(t_i) - h_{RADALT}(t_i) \qquad (10)$$

where h_{DGPS} is the height MSL and h_{RADALT} is the height AGL. Over relatively flat terrain this assumption is correct, but when the terrain roughness is large compared to the aircraft's height AGL, it is possible to read heights smaller than the position directly below the radar altimeter antennas. The height directly below the aircraft will be referred to as the *plumb-bob height*. An extreme example of the difference between plum bob height and the height measured by the radar altimeter is illustrated in Figure 5.

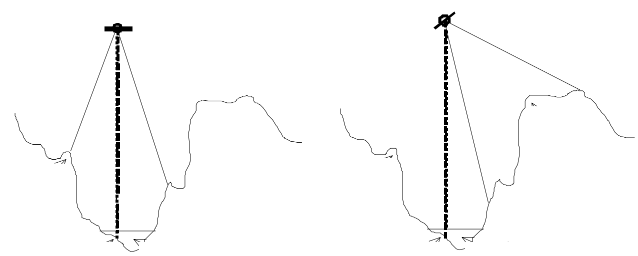


Figure 5. Effects of Uneven Terrain On Radar Return

If the measured height AGL is less than expected, it can be seen in (10) that the synthesized terrain will appear higher than the point directly below the aircraft. This effect has been observed in the flight-test data collected at AVL.

To model this effect, the calculation of the terrain database profile, h_{DEM}, has been modified; the area illuminated by the radar altimeter antenna (referred to as the radar altimeter "spot") is identified in the DEM and examined for better estimates of the radar altimeter measurements. The slant range to all of the points in this spot are computed and used to calculate the new h_{DEM}.

Pulse

To model the operation of a radar altimeter over uneven terrain, simulations were performed in MATLAB®. To model the beam coverage, the size of the coverage area is estimated by the height AGL and radar altimeter beamwidth. Equally spaced height samples are taken from the DEM; therefore the larger "spot", the more DEM samples are required. The effects of roll and pitch on both location and size of the "spot" were minimal during the Instrument Landing System (ILS) approaches examined later, and were therefore neglected in this simulation.

Slant ranges from the aircraft position to the selected terrain sample points are calculated. Conversion of the slant ranges to a time delay, τ, is not necessary since the relationship between slant range and τ is linear as shown in an earlier section. The simulation fidelity could be increased by weighting the slant ranges by the predicted propagation losses and attenuation due to grazing angle. These effects were not included in this paper because they mainly reduce the value of the longer slant ranges, whereas the radar altimeter tracks the altitude based on the shortest slant ranges. The short slant ranges represent the leading edge of the return. The minimum slant range is selected to represent the leading edge tracked by the radar altimeter.

FM-CW

For FM-CW radar altimeters, the spot size selection and range calculations were performed similarly to the pulse model. Slant ranges are not transformed into the beat frequency domain since it is only a linear transformation as shown in the description section of the FM-CW radar altimeter.

The return consists of many different ranges due to slant range and terrain effects; the frequency counter will observe many beat frequencies. It is assumed that the frequency counter in an FM-CW radar altimeter tracks the strongest beat frequency present in this return signal. To estimate the strongest beat frequency, the FM-CW model places the ranges into bins based on their range values. The range bin that contains the most ranges is selected as the range the radar altimeter reports..

Beamwidth Effects

The pulse radar altimeters (DC-3 radar altimeter and the TIFS radar altimeter) used in the AVL flight trials are fairly similar in operation. However, they performed quite differently as will be shown in the Flight Test section.. In the simulations, the only parameter that varied among both radar altimeters is the beamwidth. It will be shown that the difference in beamwidth produce significantly different results. The effect of the beamwidth on the radar altimeter output is a function of the terrain roughness and aircraft's height AGL. To estimate the effect of these parameters on the measured height AGL, Monte-Carlo simulations were run in MATLAB® for 1000 randomly selected locations within a DTED Level 1 cell (1 degree latitude by 1 degree longitude). The root mean squared (rms) errors between the plumb-bob and the minimum slant range height were plotted as a function of the beamwidth and the height AGL.

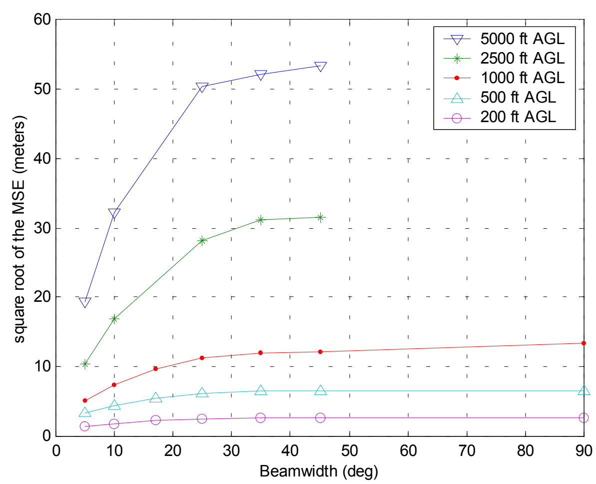


Figure 6. rms Error Between Plumb-Bob and Minimum Slant Range at AVL

The rms error between the plumb-bob and minimum slant range for the area around AVL is shown in Figure 6. The terrain roughness, σ_T, of 247 meters was calculated form the DEM. The rms error between the plumb-bob and minimum slant range for the terrain around Ohio University airport

(UNI), which has a terrain roughness, σ_T, of 31 meters, is shown in Figure 7. σ_T is a metric commonly used to estimate terrain roughness in the military for terrain navigation systems. Since the σ_T was calculated over fairly large area, a modified algorithm which measures the standard deviation of the database post heights with respect to a best fit plane through the data was used [10].

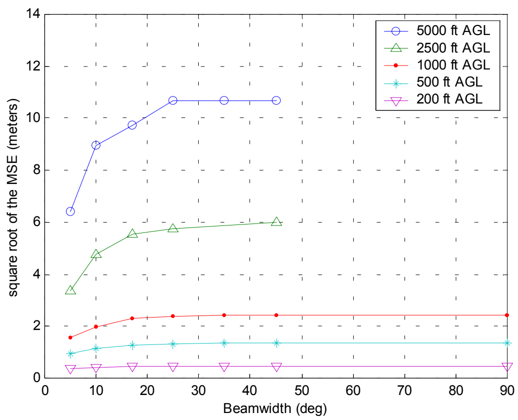


Figure 7. rms Error Between Plumb-Bob and Minimum Slant Range at UNI

Flight Tests

The two flight tests discussed in this paper were conducted by NASA and Ohio University. NASA performed the flight tests on the TIFS aircraft (see Figure 8). Kinematic GPS (KGPS) and Honeywell HG9050D2 pulse radar altimeter with a 3dB beamwidth of 35 deg., data from this test flight were used to compute the synthesized terrain profile.

Figure 8. TIFS aircraft

Ohio University flew similar approaches with different avionics on their DC-3 flying laboratory (see Figure 9). Again, post processed KGPS was used for position information, and a Honeywell HG8505DA01 Radar altimeter with a 3dB beamwidth of 17 deg. was used.

Figure 9. OU's DC-3 Test Aircraft

To compare the performance of the radar altimeters, two similar ILS approaches performed by both the NASA and Ohio University teams, were selected. Figure 10 provides a side view of the selected approaches.

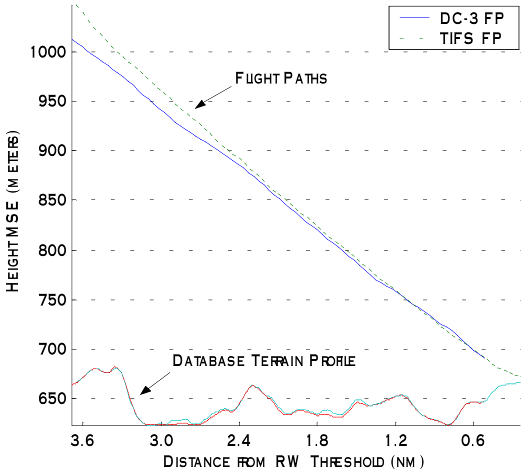


Figure 10. ILS Approach at AVL, Ohio University and NASA Flight Paths

The terrain database used in these evaluations was created using photogrammetry. The specification of the database is 4 meter post spacing with 1 meter LEP. The photogrammetry data is much more accurate than the DTED Level 1 data that has a LEP of 50m.

The synthesized terrain profile for the NASA and Ohio University approach is seen in Figure 11. It is interesting to note the large difference in the synthesized terrain produced by these radar altimeters.

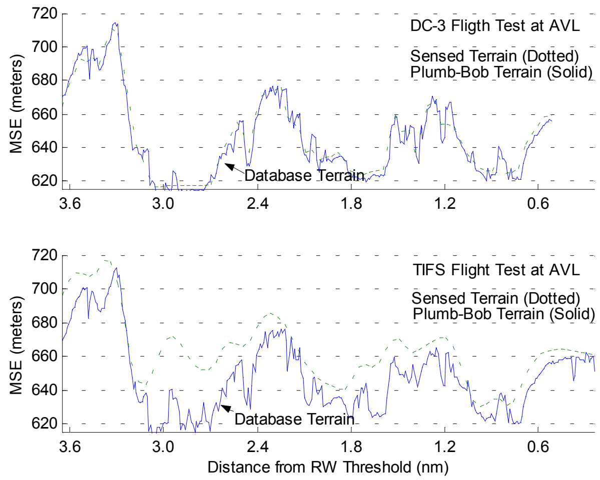
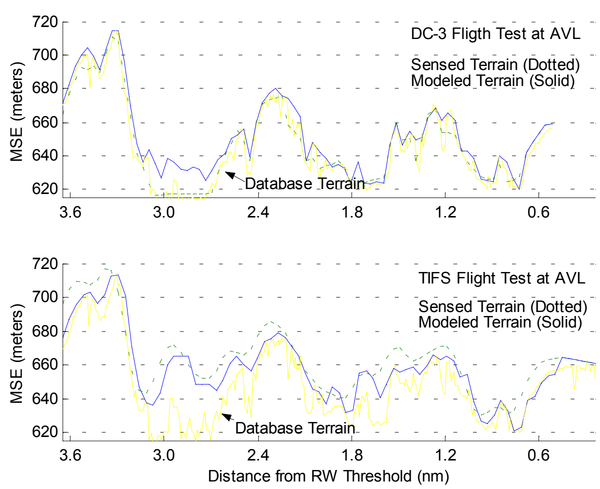


Figure 11. Plumb-Bob Database Profile and Synthesized Terrain Profile

Figure 12 illustrates the results when using the pulse radar altimeter model described Radar Altimeter Modeling section to estimate the terrain. It can be seen that the relatively course model does provide results that match the radar altimeter data



from the flight tests.

Figure 12. Modeled Database Profile and Synthesized Terrain Profile

The performance of an FM-CW radar altimeter over uneven terrain has yet to be verified for use in a terrain database integrity monitor. It is estimated, due to the logarithmic growth in slant range error as a function of beamwidth, the height AGL is similar to the heights reported by the TIFS aircraft. A chance to verify these estimations will be available in September when data will be available from NASA 757 SVS flight tests at the Eagle Vail, CO airport (EGE).

Summary And Conclusions

The performance of the radar altimeter when trying to measure plumb-bob height AGL is dependent on the beamwidth of the antenna, the height above the terrain, and the roughness of the terrain the aircraft is traversing. When designing a terrain database integrity monitor, these considerations must be taken into account when determining the nominal system error performance. Incorrect assessment of the radar altimeter error budget will cause a higher probability of fault free detection; the terrain database will be flagged when the radar altimeter measurement mechanism is to blame.

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